POSSIBILITIES OF THE PERFORMANCE IMPROVEMENT OF THE AERO- AND MARINE PROPULSION UNITS EQUIPPED WITH COMBUSTION PISTON ENGINES

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Abstract

Within the paper there have been presented the authors' opinions concerning possibilities and needs of the performance optimization of the aero- and marine units powered by piston engines both of "classic" and contemporary construction. There have been also discussed the reserves contained within combustion piston engines which enable its performance improvement (the power and specific fuel consumption) as well as the fulfillment of the ecological requirements.

Keywords: transportation, powered unites, aero- and marine combustion piston engines.

1. Introduction

The common application of combustion piston engines as a propulsion of motorcars (there were about half a billion cars in Europe, USA and Japan on 2000), truck, lorries, working machines, stationary industrial aggregates as well as the vessels, airplanes, helicopters etc. requires undertaking optimization tasks of their cooperation with the power receivers. It goes without saying that the most important task concerns the minimization of the specific fuel consumption as well as the emission of noise and toxic components in the exhaust.

The contemporarily applied constructional solutions of engines, used materials and production technologies as well as operation strategies enable multiplying the engines' durability in comparison to one achieved in fifties of the previous century. Thanks to the application of electronic systems a classic idea of the low-pressure fuel injection has become more popular assuring, among the others, the constant mixture composition, close to stechiometric one (controlled by a signal of the "lambda" probe) as well as the selection of the ignition advance angle which depends on the current engine's load [8, 16]. The progress in construction of the electromagnetic micro valves made it possible to introduce the complex, digitally controlled, fuel dosage directly to the engine's cylinders by means of high pressure injectors. The next

achievements within the range of enlarging the combustion process efficiency, spreading the engines turbocharging systems and also, the progress in the scope of computational methods concerning the endurance of constructions which subject to changeable loads, including thermal loads - permit obtaining larger powers of engines from the unit of cylinder displacement.

Development of control systems represents the next, significant step in the domain of above mentioned propulsions. Such systems permit taking into account the more and more large number of parameters influencing on the efficiency of thermodynamical processes worked out in combustion engines. Introducing hybrid drives in vehicles permits the engine users to limit a range of the combustion engine performance to such, near which, the specific fuel consumption is the smallest. Today there can be imagined a similar solution of the helicopter propulsion aided with of a solar energy from the batteries.

The adaptation of combustion engines to renewable bio-original fuels (alcohols and oils) represents the separate problem in the further engines' development (also turbine engines).

2. Profiles of contemporary engines

Constructions of cylinder heads and timing gear as well as an application of the turbocharged compressor represent the most essential constructional solutions shaping the profiles of contemporary engines. At present, the engine constructions with four valves in the cylinder head (two inlet and two outlet valves) have been almost exclusively applied within the group of unsupercharged engines for many years. Such a solution of the timing gear was introduced in aviation just before II World War [11]. By this way a good cylinder filling-up and high power of the engine at the maximum rotational speed could be achieved. It represents the most required feature in terms of the airscrew propulsion. But on the other hand, the engine's filling-up within the range of low and medium rotational speed is much worse than one in the engines equipped with a singular inlet valve. It results from feedback flows appearing in the initial phase of unlocking the valves as well as in the final phase of their closing. This was explained on figure 1.

A „four-valve" construction of the cylinder head aims to increase the inlet valve opening area – it is usually bigger by 50% than one in the classic construction.
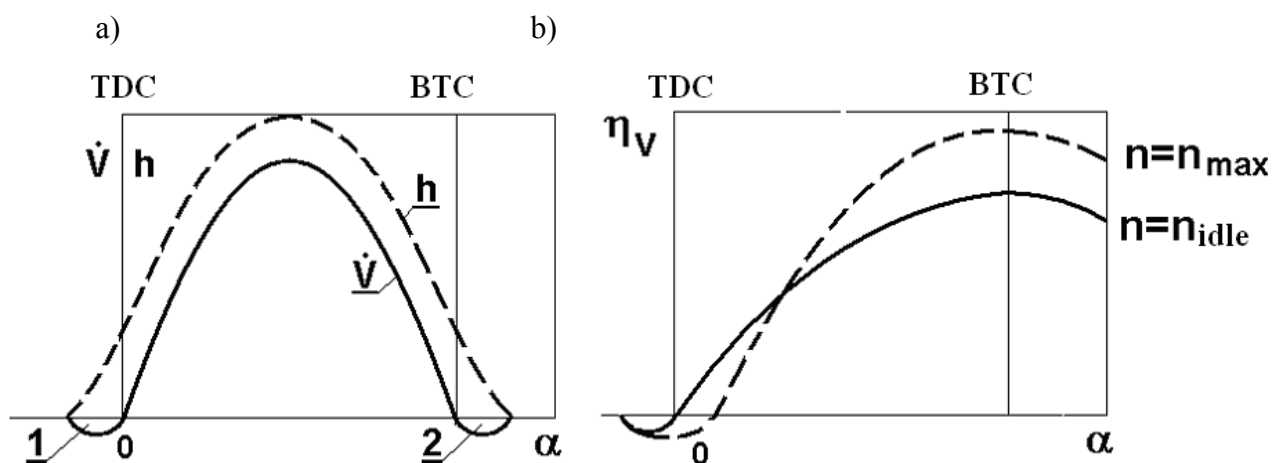

Fig.1. Flow relation between the inlet valves' slot and the angle location of a crankshaft α:
a) valve lift h and volumetric air flow rate through the valve V;
b) instantaneous cylinder filling-up coefficient η_V for different rotational speed of the engine's crankshaft n;
(1, 2 – feedback flows).

In figure 2 there is presented the relationship between a torque (proportional to the measure of filling-up the cylinders) and the engine's rotational speed while the engine has got the heads equipped with singular inlet valve and two inlet valve in every cylinder.

As the result of enlarged feedback flows through two inlet valves the reduction of torque value within the range of low and medium rotational speed can occur. However within the range of high rotational speed the positive effect of such an arrangement appears, making possible to utilize the smaller flow resistances more efficiently (the larger slots) as well as the inertia of speeding-up stream of inlet air in the final phase of closing the valves. In the consequence of such
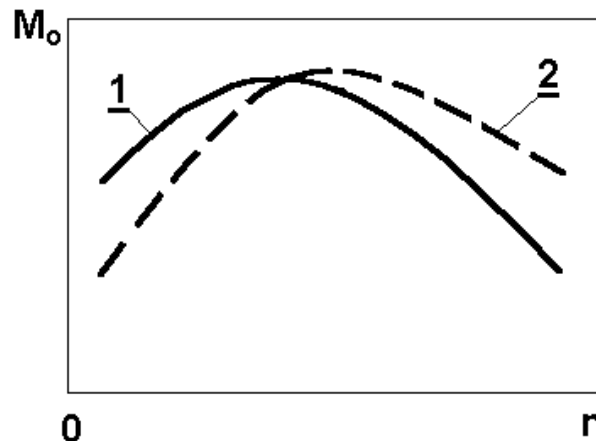

Fig. 2. Dependence between the engine's torque **Mo** and crankshaft rotational speed **n**:
1 – singular inlet valve in the cylinder head; 2 – two inlet valves.

a phenomenon the maximum power of engines equipped with "for-valve" heads is larger in comparison to engines with "two-valve" heads of the same cubic capacity [12].

3. Optimal ranges of the engines work

The strong requirements (from the ecologic and economic point of view) relating to a minimization of the fuel consumption could be fulfilled by means of precise knowledge of the general engine profile (also called the universal profile) [5]. The example of such a profile is demonstrated in figure 3. The profile's course is typical for all combustion piston engines. The differences concern only the numerical values of rotational speed, specific fuel consumption and torque. It is worth pointing out on the well-known fact that minimum values of the specific fuel consumption exist while the torque achieves the maximum values (the engine is the most efficient). When the users of vehicles, ships and airplanes possess the knowledge of this engine's feature and try to implement this theory into practical utilization, by keeping-on the rotational speed within the range Δn_{opt}, the fuel consumption and quantity of exhaust expelled to atmosphere could be significantly reduced.
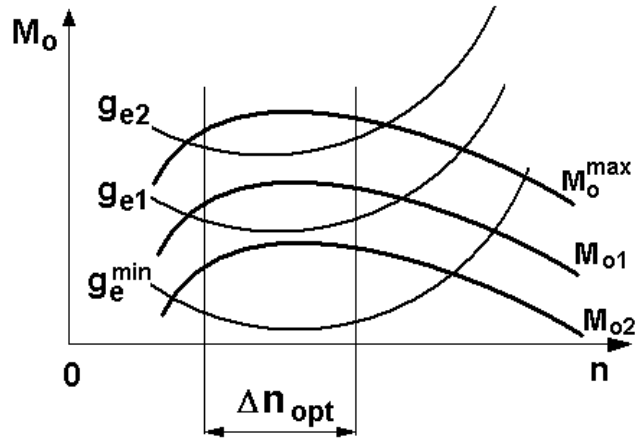
Fig. 3. General engine profile: **Mo** – torque; **n** – crankshaft rotational speed; **ge** – the line of constant values of the specific fuel consumption; **Δn**opt – the recommended range of rotational speeds.

The airscrew propulsion with a piston engine is often designed in the way that the most often used ranges of airplane speed and flight altitude as well as the airplane mass are assumed. The profiles of a necessary thrust and required power are assigned for such conditions and then, the airscrew of nonadjustable blades is matched ensuring the largest efficiency of the whole propulsion system [4]. The cooperation of piston engine with constant-pitch screw propeller has got the similar course in the marine propulsion systems.

The profiles of the unsupercharged engines and airscrew shown in fig. 4 represent their cooperation as a propulsion system of the airplane. It is easily visible, that the implemented engine works within the narrow range of rotational speeds and load alteration. However, the engine has also assure the stable and reliable running in the idle, during the airplane take-off, quick diving, and also during transient sates (acceleration and deceleration) in every environmental conditions. It also results from the data in figure 4, that every departure concerning real working conditions from the assumed ones by the airplane (or vessel) can generate significant differences between the current torque reception by the airscrew and engine's possibilities*(ΔM=Me-Msc)*. As a consequence the specific fuel consumption gets higher. Thrust alterations of the screw of unadjustable (constant) blades in flight conditions can be worked out by changing the rotational speed through controlling the flow intensity of a fuel-air mixture via a carburetor or controlling the flow intensity of air in engines of a direct fuel injection to cylinders (it concerns spark ignition engines - as experiences show that, on the average, from 1 g/s air flow intensity to the engine cylinder about 1 kW of power could be gathered).
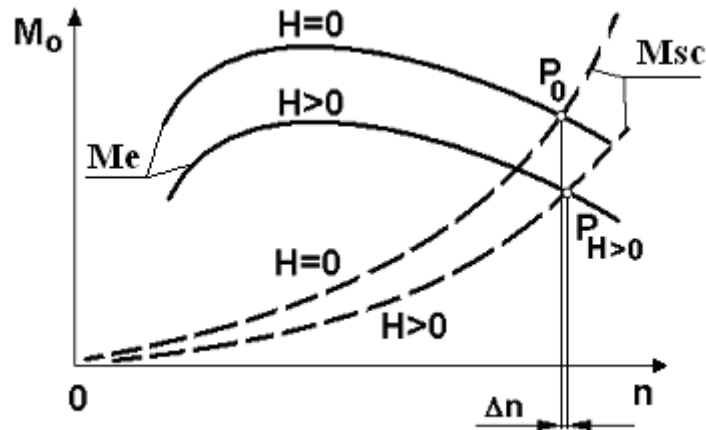
Fig. 4. Dependence of the engine's torque *Me* and the constant pitch screw's anti-torque *Msc* on the rotational speed *n* (*H* – flight altitude; *Po* – cooperation point between the screw and engine in ground conditions; *PH>0* – cooperation point between the screw and engine in flight condition).

An application of the control pitch airscrew enables wider possibilities of the efficiency enlargement in the propulsion system. It makes the engine possible to run in the range relating to the smallest specific fuel consumption and the well-chosen pitch of an airscrew responds to its maximum efficiency. This principle is explained on fig. 5. However, an operation practice of the contemporary propulsion units of small airplanes applied in aviation servicing for the sanitary, police, firefighting needs as well as in disposable aviation makes such a way optimization of the cooperation between a piston engine and airscrew impossible. Such the operational practice results from the fact that the carburetor engines are still mostly used and the control system is hand operated. As a consequence, practical activities come down to the selection necessity - by the pilot in given flight condition - of the appropriate power (the rotational speed) of the engine, airscrew pitch, composition of mixture (with regard to discrepancy between quick, significant changes of the air density and small, little changes of the fuel density in terms of flight altitude), and also the intensity of cooling the lube oil and heating-up the inlet air in the favorable condition of icing the carburetor throat [2]. In the effect, a control system of the propulsion system consists from many levers (at least four or five), and the "hand" optimization of such a system is practically impossible even for a high qualified engine-expert (a pilot absorbed with the realized task and safety assurance of the flight is able to alter the position of individual levers only step by step).
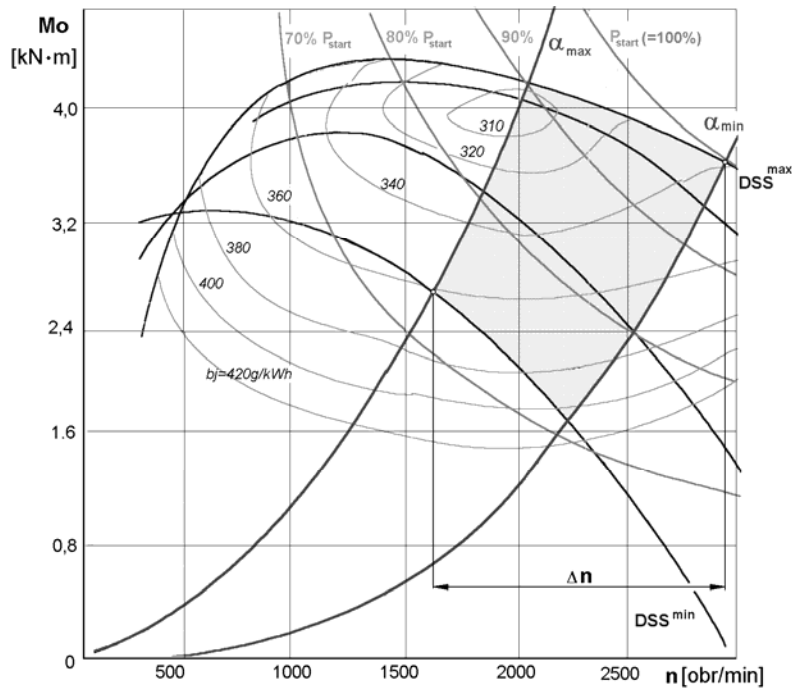
Fig.5. Dependence of the engine's torque and the control pitch screw's torque on the rotational speed **n** (DSS – a position of the control lever of the engine power; α – an angle of screw blades setting; **Δn** – the range of rotational speed alteration during flight

Several years ago in the Institute of Aviation this system was improved [1], making possible the controlling process with only one lever. The modernisation was carried out by means of contemporary electronic systems - measuring and executive. An idea of this control system is presented in figure 6. It was checked on "Franklin 4A-235" engine and then it was adapted to the propulsion system consisting of Avco Lycoming 0-360 A1A engine and the control pitch screw.

The usage, in a common aviation (*General Aviation*), of the automated control systems of the propulsion systems "piston combustion engine along with control pitch screw" type will be probably continued with an adaptation of technical achievements which have been operated in automotive propulsion for years: engines' fuel feed systems equipped with the low pressure fuel injection and the electronically controlled ignition. The slowness of an implementation of the modern technique, based on electronic elements, in so called "piston aviation" (the "conservatism"- despite that nowadays the turbine engines are commonly controlled with the microprocessor systems FADEC type) results from the necessity of obeying recipes and procedures to assure the flight safety in difficult to controlling the area of civil aviation in small companies operating the individual agricultural, touristic or sport airplanes.
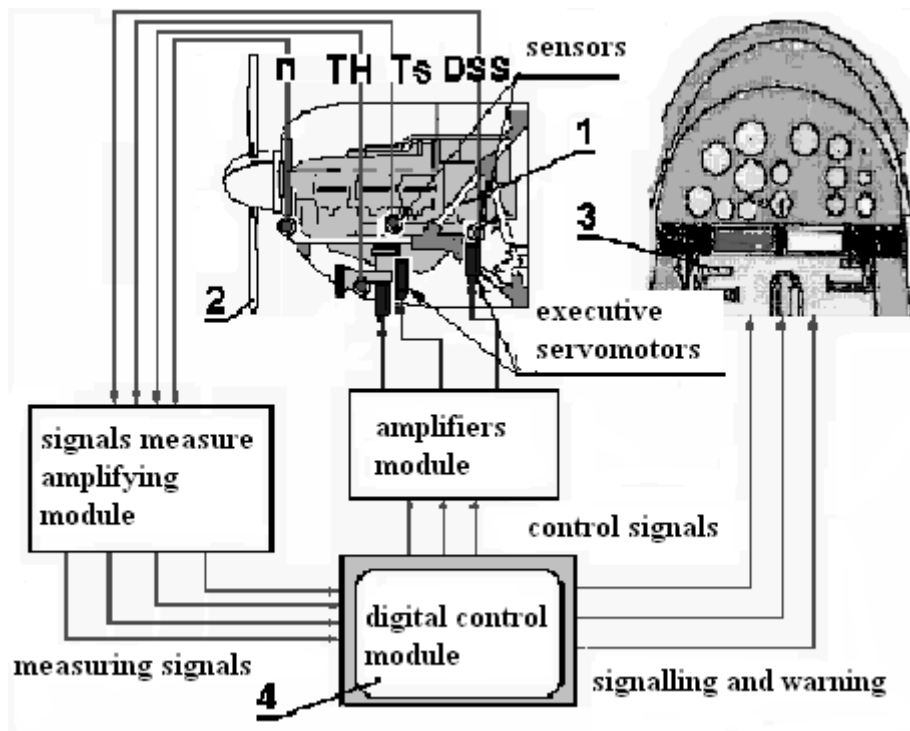
Fig. 6. Schematic diagram of automated controlling the airplane propulsion system:
1 – piston engine; 2 – control pitch screw; 3 – a lever of controlling the power; 4 – electronic
control unit; *n* – rotational speed; *TH* – ambient temperature; *Ts* – exhaust temperature; DSS – a
position of the control lever of the engine power.

4. Reserves existing in air piston engines' performance

The top of air piston engines' development was practically reached in half of last century. It that times a prototype of the "Nomad" engine was designed and built by the British company Napier. It was 12-cylindrical, self-ignition engine at a push-pull arrangement of cylinders ("boxer"). The maximum power equaled 3050 kW (achieving 73,5 kW of power from 1 dm^3 of the engine cubic capacity), specific fuel consumption - 230 g/kWh and unitary mass - 0,53 kg/kW. The engine was supercharged by means of a multistage axial compressor driven by the engine's crankshaft. Such the engine construction contained also an axial turbine, powered with escaping exhaust, which gave back the power on the crankshaft across the toothed gear and hydraulic coupling. This way of driving the compressor (assuring "keeping up" a compression against a rotational speed of the engine crankshaft) and using the turbine's power made it possible to shorten the time of acceleration process and assure the stable engine running during the deceleration process. This solution outdistanced the contemporary productive practice by almost half a century. In spite of so good performances in comparison to constructions of aviation leading companies of II World War times: USA, USSR and Germany (the unit power usually did not exceeded 37 kW from 1 dm^3 of the engine cubic capacity) the "Nomad" engine lost the competition with the violently developing turbine engines: airscrew and helicopter, which achieved the similar power at the smaller personal mass, overall dimensions and the simpler construction. The project was finished in April 1955.

Piston engines contemporarily used in aviation dispose powers that are many times smaller than the Napier "Nomad" engine. The majority of them are unsupercharged engines, construction bearing elements of which are not very high loaded. However, almost an absolute working

reliability and large durability are required from them, and additionally the newly projected engines have to fulfill the more and more sharper norms concerning exhaust toxicity. The reduction of a noisiness level during take-off and flight on small altitude level has aimed recently. The reserves exist in each of them. They can be used by modernizing the construction on the basis of a present knowledge about the aerodynamics, combustion theory, gases filtration in cleaners, load exchange in cylinders, theory of fluid-flow machines (compressors and turbines), and at last about dynamics, construction endurance and the new materials. For several years these disciplines have represented scientific penetration fields in both of the aspects - theoretical and experimental. The common accessibility of contemporary computational and measurement tools permits their further development.

As far as the issues relating to the engine's fuel feed systems are concerned the closest future of such engines will deal with exchanging the carburetor supply for direct fuel injection into cylinders with doses controlled by an electronic system (sometimes an opening the electromagnetic injectors), or for the low-pressure injection with a catalytic afterburner and the control system making use of a signal from oxygen sensor in exhaust (the "lambda" probe). However, it will be possible after introduction of the leadless aviation gasoline into operation (maybe the wider usage of "biofuels" containing ethanol), because neither the catalytic afterburners nor the "lambda" probes can not work properly (they "poison" themselves) in engines feed with gasoline containing the lead tetraethyl - and just such a petrol (the Avgas) is universally applied in aviation.

Independently from above mentioned issues, every one of the engine has got a reserve in the range of unification possibilities of the flow resistance in all the cylinders' inlet passages aiming the obtaining an equal filling-up and equal power - the engine smoothness. It is possible through the suitable selection (e.g. experimental) of inlet pipes' shape and dimensions [12]. The analogous proceeding with outlet passages channels will permit receiving the equal content of exhaust remainders in the engine's cylinders - which also influences on a degree and equability of the filling-up. Moreover, it has got also impact on the combustion process and the content of toxic components in exhaust. The positive results obtained in these ways could be very simple in case of radial engines and a little bit more difficult as for the in-line engines.

There has been also observed a significant, positive influence of the strong rotating load on the process of inflaming the mixture in engines' cylinders of the spark ignition - it is explained on figure 7 presenting the simplified case of one sparking plug (the ignition systems with two sparking plugs for every one of engine are applied in aviation) [6]. An extension of the discharge time on sparking plug's electrodes from several microseconds (at the inconnector initiation) to a few hundred microseconds at the usage of an electronic ignition system is in favour with the fuller utilization of the axial-symmetric whirl in the engine's cylinder. A peripheral speed of the whirling load in relation to sparking plugs should be greater than the speed of moving the flame's forehead in a mixture.

A noise emission of the engine might be considerably limited by means of an application of dust extractors of inlet air, e.g. multicycloned (at the effectiveness level of 95%) which is sufficiently remote from the engine. This way is more and more often used in large trucks (TIR). The introduction of a catalytic afterburner not only limits a content of nonburnt hydrocarbons, but reduces the noisiness of expelled exhaust. The similar result is gained in SI engines (self ignition) of trucks in which the exhaust filters stopping the soot have been applied.

A noise could be limited in every engine by introducing an ejector in exhaust passages (compare fig. 8). The silencers with two exhaust pipes at the large diameter installed in "tuned" automobiles have only a slight impact on decreasing the dirt of load with exhaust remaining from the previous cycle (a coefficient of the exhaust's rest). Such pipes influence on the power enlargement in a small degree. Only the lowering a frequency of the emitted noise represents the most essential effect resulting from this engine's modification.
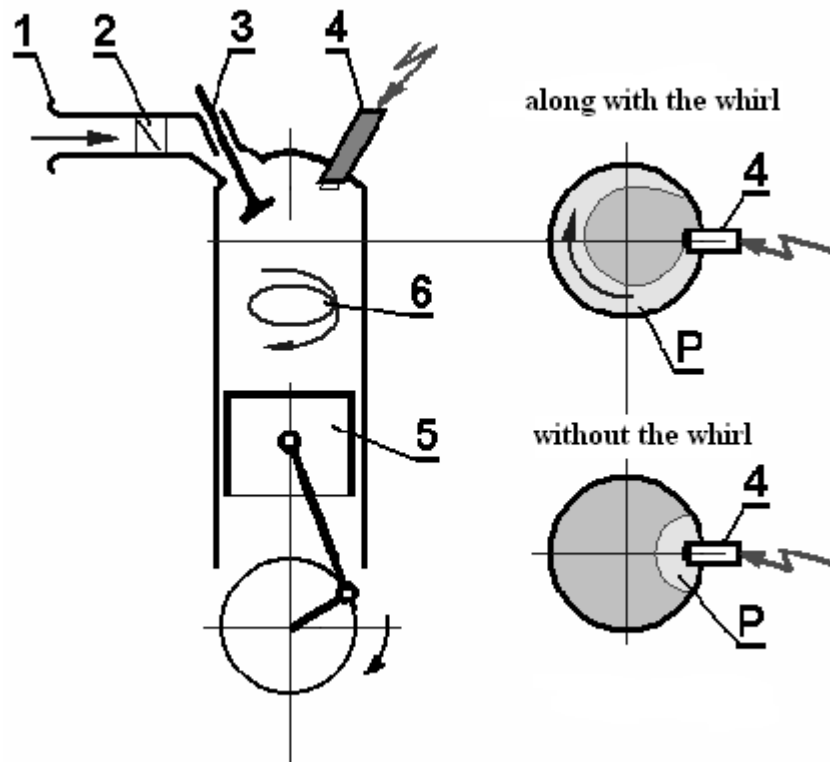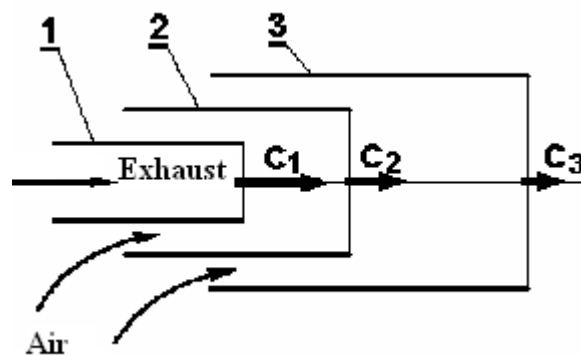
Fig.7. The load whirl in the engine's cylinder:
1 – inlet channel; 2 – screw whirler; 3 – inlet valve; 4 – sparking plug; 5 – piston; 6 – whirl in the cylinder; P – inflaming area.

Rys.8. Ejector of the exhaust passages
(c_1, c_2, c_3 – exhaust flow velocity and flow velocity of exhaust mixed with ejected air)

An application of the supercharged compressor represents the radical way of a power increase of the combustion piston engine. It is usually a radial compressor driven by the turbine (turbocompressor), in which the energy of escaping exhaust is utilized [10]. The application of a turbocompressor instead of the compressor driven by the engine's crankshaft improves the general efficiency and configuration of a whole propulsion system, because enables a location of the turbocompressor not necessarily in direct closeness of engine' heads. Nevertheless, these fluid-flow machines fine tuning is difficult, particularly for piston engines at the number of cylinders smaller than 5. It results from their gasdynamical originality. From one's nature the piston engine are characterized by the strong flow pulsations in inlet passages (receipt from the compressor) and exhaust passages (powering the turbine) and the compressor sa well as turbine are machines of the
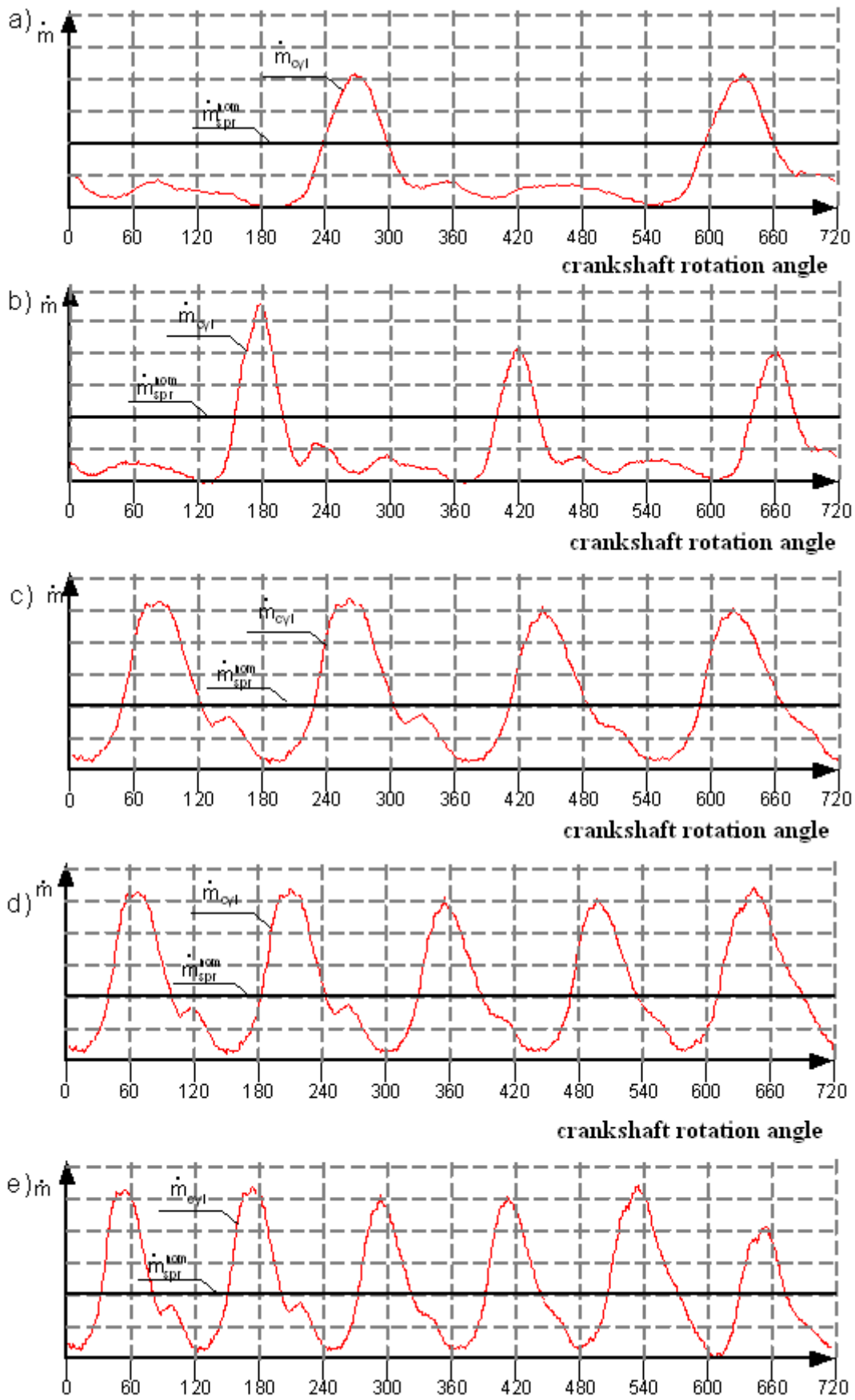
Fig. 9. Courses of the fluid flow intensity in inlet passages of the piston engine:
a) 2-cylinder; b) 3-cylinder; c) 4-cylinder; d) 5-cylinder; e) 6-cylinder.

continuous flow. The courses of a temporary flow intensity of air in inlet passages of piston engines of different numbers of cylinders in dependence of position of crankshaft's angular position and resulting from here the flow pulsations in a inlet collector are shown in figure 9. These phenomena, i.e. the affected pulsations of stream and periodical flow throttling are in favour with appearing the compressor's unsteady work (the local stream tearing-off phenomenon on the blades' profiles). Additionally, they also cause also lowering the efficiency of filling-up process in cylinders. It is well-known that the smaller is the existing pressure in front of an inlet valve during its opening the smaller is a working medium density and mass of the fresh load (the filling-up efficiency gets smaller η_v). Hence, there should be aimed to "tune-up" the pressure pulsations of air in the inlet channel of a multi-cylinder engine to the position of inlet valves of individual cylindrical sets in order to assure approaching the overpressure waves during maximal valve lift. It is worked out through grouping cylinder connection into common inlet channel as well as the suitable selection of its length. From the data presented in figure 9 result that only in the case of engines at the number cylinders equals 6 (and more) the good conditions of co-operation between the engine and turbocompressor can be expected.

In order to evaluate the conditions of co-operation between the engine and compressor of the supercharging system (the most often radial) there should be associated the compressor's universal profile i.e. a dependence of the compression ratio π_S on the fluid flow intensity of air $\dot{m}_{spr}$, within the background of contour lines of the constant efficiencies η_{eS}^*, with a profile of the network cooperating with the compressor S. This profile represents a flow resistant curve, as a resultant of the engine capacity curve, flow channels along with a filter and radiator of the charging-up air and also the compressor's diffuser (compare fig. 10). A well-chosen compressor should be characterised with the steady work at all the possible engine's loads and the possibly highest efficiency.

How it results with cooperation line courses, drawn on figure 10, the fulfillment of such a condition is only possible when the inclination of the network profile is similar to the inclination of the compressor's profile. Moreover, the network profile has to run in an appropriate distance from the border of instable work (the surging line). The higher is a flow resistance the more ornate becomes the network profile favouring with the getting the maximum compressor efficiencies. Nevertheless, because of worked out transient processes and diverse accumulation features of the turbocompressor's rotor mechanical and thermal-flow system, the margin of the compressor steady work should not be exceeded by more than 10% of the minimum value.

In case of the force growth of load (the quick acceleration) the four-stroke engine is especially threatened with the phenomenon of unsteady compressor's and in case of sudden changing the load on the small one (the deceleration) - the two-stroke engine. It results from a nature of the flow resistances courses for the network with the four-stroke and two-stroke engine - the dashed lines 1' and 2" on figure 10.

Furthermore, the exhaust pressure wave, which the amplitude depends on a pressure in the cylinder and a speed of opening the outlet valve or a speed of exposing the escape slot, is generated during unlocking the outlet valve or the slot of the engine cylinder. In the supercharged engines the exhaust escape channel is closed with the turbine guide of precise determined active section of flow, guaranteeing a possibility of an obtainment of the maximum pressure fall and delivery of a turbine. The maximum efficiency and performance of the turbine are limited with the occurrence of the sound velocity in the guide or in the rotor (so called "clogging the nozzle"). It finds one's reflection in a convergence of the izodrom bunch on the turbine flow profile. Additionally, because of the lock of exhaust escape channel with the turbine guide, either the inreflexive flow is gained (very seldom) or a reflection in the pressure impulse in a form of the return wave improving the cylinder scavenging and consequently enlarging the engine power in a well-chosen range of the crankshaft rotational speed.
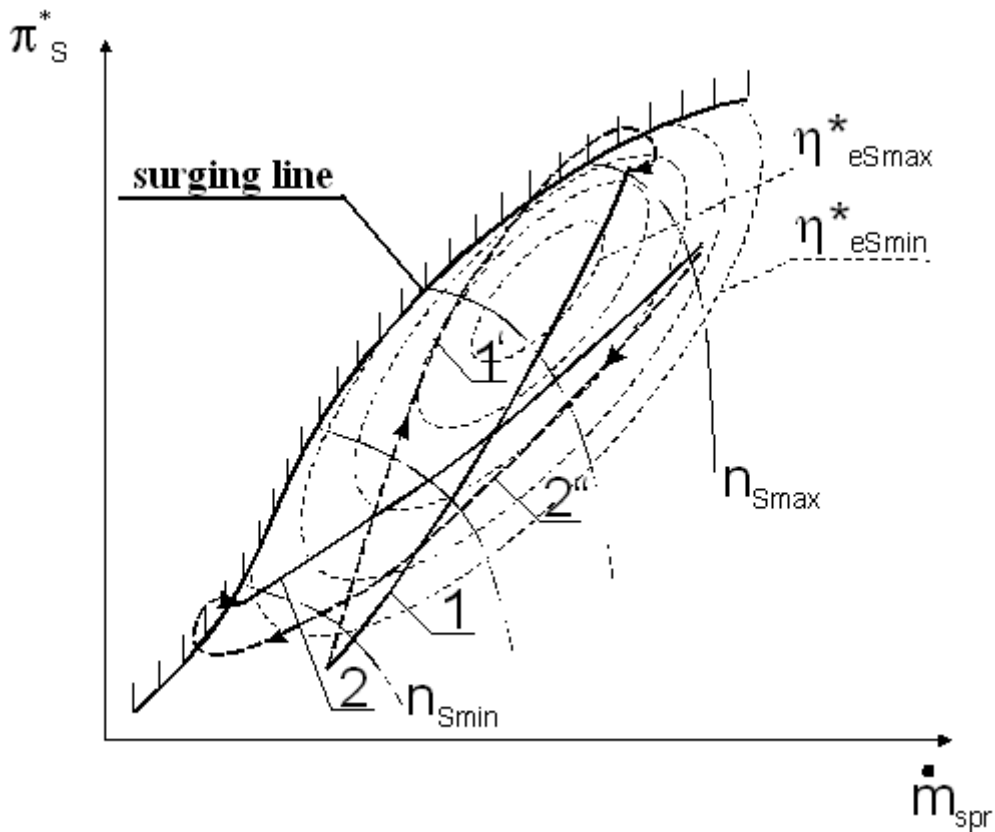
Fig. 10. A cooperation profile of the compressor and the engine flow network:

1 – network profile of the four-stroke engine in steady states;

1' – network profile of the four-stroke engine in a process of the forced load increasing;

2 – network profile of the two-stroke engine in steady states;

2" – network profile of the two-stroke engine in a process of sudden load drop;

$\eta^*_{eS\,max}, \eta^*_{eS\,min}$ - lines of the same values of the compressor efficiency;

$n_{S\,min}, n_{S\,max}$ - lines of the compression ratio profiles at constant values of the turbocompressor rotor rotational speed (izodroms).

The pulsating course of a flow intensity in the exhaust escape channel as well as the fact, that a capacity of the turbine guide vanes is chosen by the constructor to averaging flow intensity affect (similarly to the compressor) the lowering the turbine efficiency and the extortion of vibration of the exhaust stream which are shifted in relation to air stream vibration in the compressor, in the whole range of the engine work, by the value resulting from timing angles. In this place, the conditions of the engine's cooperation with a turbine of the turbocompressor could be also significantly improve by the grouping connection of the engine's cylinders to separate exhaust channels circuitaly feeding the turbine. It gives the additional advantage in a form of the considerable lowering of the turbine ventilating losses. The cylinder grouping should exclude a possibility of joining these cylinders in which occurs the mutual, significant agreeing the phases of the exhaust outlet, and by then, the interference of the pressure waves in the channel. There should be also excluded a possibility of the return exhaust pumping. Such a possibility significantly grows up during increasing a counter-pressure in the channel. Therefore, the correct designing the dimensions and the form of exhaust escape as well as the flow section of the turbine guide vanes gather a key meaning (fig. 11).
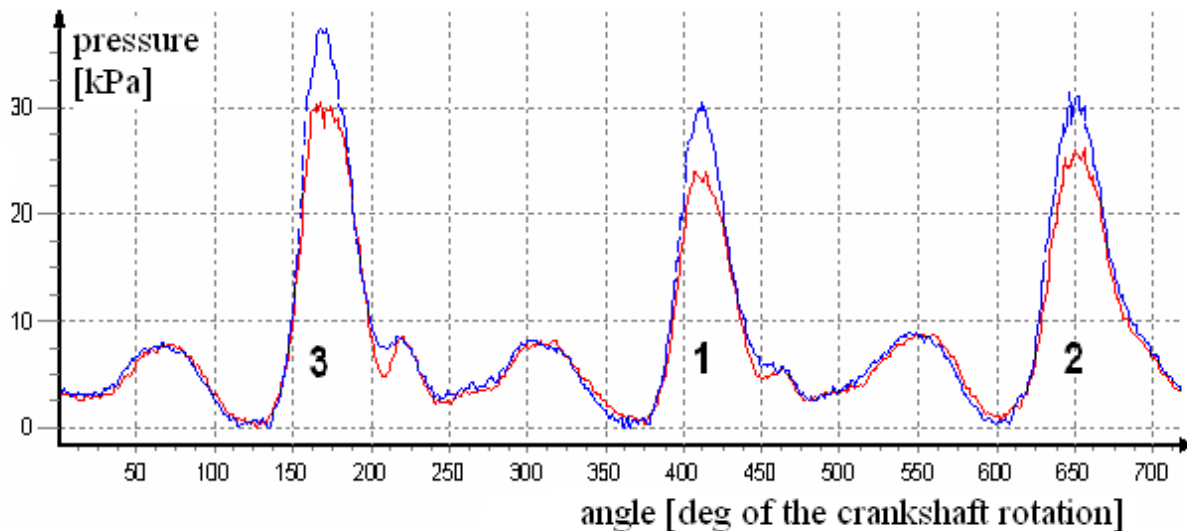
Fig. 11. Changeability course of exhaust pressure in a control intersection of the channel powering a turbocompressor in 6-cylinder engine Sulzer 6AL20/24 type, as a function of the angle the crankshaft rotation: 1,2,3 - the cylinder numbers(the courses for 3 cylinders are shown in the figure); the continuous, red line - the course of exhaust pressure changeability in the channel at a full flow patency; blue line - the course of exhaust pressure changeability in the channel at 50% decrease in a flow active section's field.

It known from the analysis of exhaust flow conditions through the turbine working in a constant-pressure supercharging system, that the flow intensity and the turbine power diminishes together with decreasing a section field of the turbine nozzle. However, within pulsating systems (Büchi) the smaller is this field the higher is an amplitude of exhaust pressure waves.

On the basis of the curves course presented in figure 11 there could be observed a considerable enlargement of the maximum values of the amplitudes of pressure waves while reducing the active flow section of the channel in front of turbine. At the same time, their angular positions in reference to opening moment of the outlet valves of individual cylinders stay almost unchanged. The energy enlargement of exhaust escape impulses leads to the growth of the turbine power, rotational speed turbocompressor rotor as well as supercharging pressure.

However, from the other hand, the growth of the exhaust average pressure in front of turbine worsens the conditions of cylinders scavenging - a counter-pressure reacting on pistons grows, which extorts the growth of energy losses on removing exhaust from cylinders.

It seems, that the theory of a cooperation of a piston engine with turbocompressor (and also with a compressor driven by the engine crankshaft and with a turbine giving back a power on the crankshaft) still expects finishing-up a scientific polishing and experimental verification. There is already known, using an engineer intuition, supported with experimental investigations of fluid-flow systems of unsupercharged automotive engines and there could be foreseen, that the optimum turbocompressor location should be sought through the appropriate selection of volumes of inlet and outlet collectors, taking into account the number of engine's cylinders.

5. Conclusion

An observation of rapidly and effectively realized modernizing the mass produced combustion engines for automobiles, trucks, working machines and military heavy caterpillar vehicles as well as an observation of a "development" state of aviation piston engines leads to conclusion that generally speaking there is still very much to do in aviation. It does not seem

possible direct transfer of the existing, already verified solutions from traction engines to aviation. It results from the aviation specific which permits implementation of such devices (only), which assure the reliability of working and flight safety in all working ranges and environmental conditions.

In aircrafts there should be taking into account quickly existed changes of the air pressure and temperature in surroundings (particularly during the take-off - with the growth of a flight altitude or during the altitude lowering - approach to landing) in distinction to the ground transport and marine propulsions. Within the altitude scope of usage of piston engines driven airplanes and helicopters a density of air changes within the range from about 1,2 kg/m3 - on the ground, to about 0,6 kg/m3 - on the ceiling and a temperature alteration (in the same flight) can reach even 70 degrees. It is worth pointing out that these changes can arise within several minutes only.

We can not require from the pilot burdened a duty of safe leading the airplane, navigation etc. to optimize a cooperation of the engine and airscrew, interfering in regulators' settings and choosing the suitable range of the engine. Such activities should be taken over by the already available automatics (successively implemented for turbine engines and applied on ships powered by control pitch propellers) which makes use of optimization algorithms of the propulsion system working ranges and diagnostic algorithms worked out by the experienced expert of aviation engines. Contemporary electronic systems enable the safe usage the propulsion system thanks to the sufficient reliability during flight (enlarged by the possibility of "doubling" connections and control components - construction redundancy) at the retaining the smaller mass and overal dimensions than the classic hydromechanical systems have. This "electronization" of control systems of the piston propulsion systems should be applied in newly arising constructions as well as in "classic" carburetor constructions in frames of modification (carried out e.g. at the opportunity of periodical repairs).

The problem of the appropriate selection of volumes of inlet and outlet channels in dependence on the cylinder number and displacement stays still underestimated. There can not be also omitted the fact that the modern control systems enable conducting a current registration of the propulsion system's working parameters and its diagnosing, which enlarges safety and reduces the overall operation costs.

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